The Search for Tin

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In this second part of his article the author deals particularly with centres of mineralisation and the genesis of primary tin, going on to consider hydrothermal zoning.

IT is a fact of some importance that whilst cusps which contain apical greisen-bordered cassiterite-bearing veins are frequently flanked by hypothermal lodes, etc., of economic importance, the cores of the cusps are usually barren: the greisen-bordered veins have only a very limited vertical extent and later veins do not normally interest the apex of the cusp. The St. Agnes and Carn Brea cusps are devoid of lodes of importance and so is that of Kit Hill (Cornwall). In the latter case this was conclusively demonstrated when the Excelsior Tunnel was driven through it, as the excavation only revealed a few ore-mineral-poor roots of the many greisen-bordered veins which occur at the apex of the hill.

Centres of Mineralisation

As centres of mineralisation are associated with well-defined cusps any distribution pattern which the latter may conform to in a given region is of considerable importance when prospecting there. In the West of England the writer has demonstrated that the tinfields and associated cusps occur at the intersections of certain approximately N.E.-S.W. and E.W. lines (which are also the dominant strikes of the hypothermal lodes, dykes and granite ridges) which correspond to the trends of the major anticlines (Hosking, 1962). It seems, therefore, reasonable to believe that the location of these cusps was determined by the moulding action of the invaded sedimentary rocks, and that despite certain views to the contrary, post tin-lode movement along the cross-courses, which are approximately at right angles to the arcuate axis of the batholith, has not greatly altered the original plan-form of the latter. Consideration of the cusp distribution pattern has already pointed to areas worthy of exploration. It is also of interest to note that the cassiterite/wolframite deposits of Portugal, as figured by Cotelo Neiva (1944), exhibit a distribution pattern suggesting that they also are centred around cusps whose sites of development were determined in much the same way as those of the South-west of England.

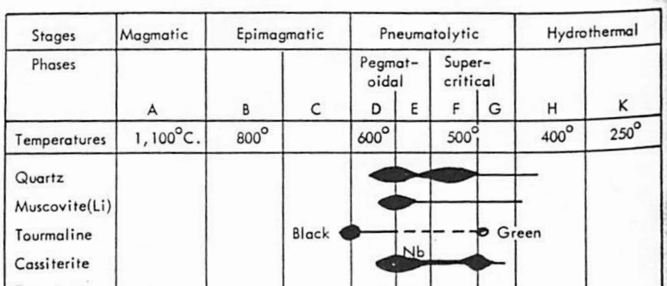
In Cornwall there is little doubt that the tin lodes are disposed along the flanks of undulating ridges and that they attain maximum economic importance in the vicinity of those points along the ridges where cusps occur. These lodes, as already noted above, are approximately parallel to each other and to neighbouring porphyry dykes, hence, having discovered one lode, further parallel lodes should be sought. Occasionally, as in the Gwinear District (Cornwall) two dyke systems with distinctly different trends may be encountered; in such circumstances the majority of the earlier lodes trend parallel to one dyke system or the other, but a few lodes may follow first one trend and then the other, and occasionally a lode may be encountered whose strike is a compromise between those of the two dyke systems.

It must be stressed, that in some tinfields the lode pattern is much more complex (it is so, for example, at the Pahang Consolidated mine, Malaya) and then exhaustive structural studies must be carried out before the likely location of lodes can be forecast with a reasonable degree of confidence. Even in such an intensively mined area as Cornwall structural studies are of the greatest value both during the search for new mines by surface exploration and for further lodes within the confines of working mines. Garnett (1961) for example, by structural studies, has demonstrated that at Geevor mine the tin-bearing lodes developed between earlier fractures, which strike at about right-angles to the former, but whose controlling action had not previously been appreciated because post tin-lode movement had taken place among them. He also suggests that the lodes of Wheal Vor (Cornwall) have developed similarly between two fault systems, which were generally believed in the past to be post tin-lode in age, and hence the chances of finding useful extensions of the rich Wheal Vor lodes outside these impounding fracture zones are negligible.

TABLE 4

PARAGENESIS OF CERTAIN STANNIFEROUS PEGMATITES OF MUMBA-NUMBI, KIVU, CONGO

(After Agassiz, 1954)



In regions characterised by epithermal or xenothermal tin mineralisation, as in central Bolivia, there is also a tendency for lodes to congregate around cusps, but in such regions, where lodes developed comparatively near the surface, the lode pattern is often exceedingly complex, and even when a number of lodes which have been "opened up" by mining has been subjected to intensive structural analysis the results often do not help materially, as they do in Cornwall, in the search for further lodes. (See Turneaure, 1960A and B).

The fact that tin lodes commonly strike parallel to neighbouring porphyry dykes and that a given dyke often has a tin-lode bordering its foot or hanging wall, or even within it, can be of considerable aid to the prospector, particularly in an area whose geology is imperfectly known. In such a case, if a porphyry dyke is located, and in the absence of evidence to the contrary, it is worthwhile assuming that the strike of any tin lodes present is likely to be approximately parallel to that of the dyke and that the area in the immediate vicinity of the dyke itself is worthy of particularly close examination. Long ago Carne (1818) realised that a study of hypothermal lode dyke relationships was of considerable importance to those searching for ore and he noted that lodes commonly occur along the foot or hanging walls of such bodies and even within them: he also observed that when a lode intersects a dyke the former may increase or decrease in richness, that on occasion it may act as a feeder to a stockwork within the igneous body and that sometimes the lode may be locally deflected by the dyke in such a way that the dyke appears to have faulted the former. The following are typical examples of lode dyke associations:

Redmoor Mine (*Callington, Cornwall*). A tin lode occurs along the foot-wall of a porphyry dyke.

Geevor Mine (*Cornwall*). The Coronation Lode is markedly deflected at the No. 8 horizon by a granitic dyke, and after following the trend of the latter for c. 60 ft. it breakes through the deflector and assumes its normal trend.

Wherry Mine (*Cornwall*). Here a rich tin-bearing stockwork developed where a "normal" lode intersected a porphyry dyke.

Parbola Mine (*Cornwall*). A tin-bearing stockwork occurs virtually entirely within a porphyry dyke.

Mount Pleasant Mine (*New Brunswick*). The richest cassiterite-bearing deposit yet encountered is at the contact of what is probably a highly kaolinised dyke with the invaded volcanics.

Genesis of Primary Tin

Emmons (1940, pp. 185-194) suggests that during the crystallisation of a granitic magma "pools" of residuum collect under the "high spots" of the roof, and as this takes place so a vapour pressure develops which may reach such a magnitude that the overlying rocks are fractured, and the residuum, which is thus enabled to escape, entirely or in part, is instrumental in the formation of mineral deposits. If fracture takes place at a comparatively early stage, before the "granitic" components have been completely eliminated from the liquid phase, pegmatites develop: if fracture is delayed somewhat, the escaping products cause the generation of hydrothermal bodies, and if the vapour pressure never exceeds that of the confining rocks the residual liquid remains within the cooling igneous mass where it may react with the granitic minerals effecting marked changes and its heavy metal ions may be incorporated in part, or entirely, in the new silicates: alternatively the heavy-metal ions may report in new accessory minerals which may be disseminated and/or locally concentrated in the igneous mass. Thus, in the last case, tin may be incorporated, in part, at least, in secondary micas; it might report as disseminated cassiterite grains (as in parts of the Nigerian Plateau), or, on comparatively rare occasions, as in the Potgietersrus tinfields of South Africa (Strauss, 1954, pp. 141-147) it may segregate as cassiterite, together with species commonly found in hypothermal lodes, in pipes just beneath the granite roof.

If Emmons' postulate is correct it follows that magmatic disseminations and segregations, pegmatites, and hydrothermal lodes and replacements are the types of orebody to be expected. It also suggests that in an area of limited extent major tin-bearing hydrothermal orebodies and large pegmatites *of the same age* tend to be mutually exclusive. This is, in fact, generally borne out by field observations: in the Wamba area of Northern Nigeria, in the Geomines district of the Belgian Congo, and in the Kamativi field of Southern Rhodesia, economically interesting concentrations of cassiterite are virtually confined to the pegmatites: in Cornwall, on the other hand, numerous tin-bearing lodes occur but tin-bearing pegmatites have but seldom been recorded and all known examples are small and of little or no real economic importance. In the Rooiberg field of South Africa tin occurs only in lodes and replacements.

However, in order to stress the fact that the presence of important stanniferous pegmatites does not automatically exclude the presence of useful tin-bearing lodes of the same age it can be stated that in the Mumba-Numbi region of Kivu, Belgian Congo, (Agassiz, 1954) a number of tin-bearing veins, of some importance, occur in the same general area as stanniferous pegmatites: the veins, however, by comparison with the Cornish lodes, are poorly mineralised.

TABLE 5

GENERAL ORDER OF DEPOSITION, ETC., OF THE CORNISH LODE MINERALS

(After Hosking and Trounson, 1959)

Gangue	Zone	Ore-Minerals		Economically important Elements	Composition of Wolframite and Sphalerite	Trace Element Data *
		Latest Minerals				
Calcite, Chalcedony, Quartz	7	Barren: (pyrite)	MESOTHERMAL AND EPITHERMAL LODES Generally at right-angles to granite ridges			
Calcite, Chalcedony, Quartz	6	Hematite Stibnite Jamesonite Tetrahedrite Bouranite. Pyrargyrite? Siderite Pyrite: (marcasite)		Fe Sb		
Dolomite, Chalcedony, Quartz	5b	Argentite Galena Sphalerite		Ag, Pb Zn		↑ Bi and Sn decrease in galena
Dolomite, Barite, Chalcedony, Quartz	5a	Pitchblende Niccolite. Smaltite Cobaltite. (Native bismuth: bismuthinite?)		U, Ni, Co Bi	↑	↑
Fluorite, Chlorite, Hematite, Quartz	4	Chalcopyrite Sphalerite Wolframite: (scheelite) Arsenopyrite Pyrite	HYPOTHERMAL LODES Generally parallel to granite ridges and dykes	Cu	Fe increases in wolframite & decreases in sphalerite	Jn, Mn, & Sn decrease, and Ge & Ga increase in sphalerite
Fluorite, Chlorite, Hematite, Quartz	3	Chalcopyrite: (stannite). Wolframite: (scheelite) Arsenopyrite Cassiterite (wood tin)		Sn W As		
Chlorite, Hematite, Tourmaline, Quartz	2	Wolframite: (scheelite) Arsenopyrite: (molybdenite?) Cassiterite				
Tourmaline, Quartz	1	Cassiterite Specularite				
Tourmaline, Kaolinite, Quartz	Greisen-bordered veins	Arsenopyrite. Stannite. Wolframite Cassiterite	Veins often in granite cusps			
Felspar, Mica, Tourmaline, Kaolinite, Quartz	Pegmatites	Arsenopyrite. Wolframite Cassiterite.				
		Earliest Minerals				

* See El Shazly, E. M., Webb, J. S. and Williams, D. Trace Elements in Sphalerite, Galena and Associated Minerals from the British Isles. Transactions Institution of Mining and Metallurgy, LXVI, 1956-57, 241 - 271

Emmons' views also provide a basis for the following suggestions as to why large hypothermal lodes commonly flank cusps capped by greisen-bordered tin veins. It seems reasonable to believe that the greisen-bordered vein-swarm developed from a pocket of residuum derived solely from differentiation of the magma of the cusp. Later, as the batholith as a whole consolidated from the margin inwards, large "pools" of residuum collected beneath the "high-spots" of the roof, that is, immediately below the cusps, which, provided they were "tapped" by the development of fractures, were capable of effecting the formation of much larger ore-bodies than could possibly develop from the small "pools" derived from the limited magma of the cusps themselves.

There seems little reason why Emmons' postulate (with, perhaps, certain modifications noted below) should not apply to the development of all types of primary tin deposit regardless of whether the igneous parent is near, or at a considerable depth below the surface. Certainly in Bolivia the xenothermal lodes are commonly associated with cusps or their equivalents the volcanic pipes, which sometimes contain in their uppermost horizons (as at Potosi: see Turneaure, 1960, pp. 238-239) numerous mineralised veinlets which are approximately equivalent to the greisen-bordered veins of Cornwall.

Despite the elegance of Emmons' views concerning the genesis of lodes, etc., evidence is available which has led some to reject them and has prompted the writer to suggest that they may need, at least, some modification. Barsukov (1957), as a result of extensive mineralogical and analytical studies holds that tin deposits (at any rate, the greisen-bordered types) owe their development essentially to the release of tin from the biotite in the granite by ascending solutions rich in sodium and fluoride ions, its transportation to major channel ways as $Na_2Sn(OH, F)_6$ and the subsequent deposition of cassiterite in accordance with the following equations:

$$Na_2Sn(OH\,F)_6 + 2H_2O = Sn(OH)_4 + 2NaF + 2HF$$
$$Sn(OH)_4 = SnO(OH)_2 + H_2O$$
$$SnO(OH)_2 = SnO_2 + H_2O$$

He claims that below the roots of the lodes he investigated the granite is strongly albitised and that the potential of a lode below a given horizon can be broadly determined by a mineralogical examination of the wallrock at the horizon in question, combined with a study of its tin content.

Whether Barsukov's claim is absolutely correct or not, is less important than his underlying suggestion that by appropriate mineralogical and chemical studies the potential of a lode below a given horizon may well be capable of assessment: clearly this idea merits exhaustive examination.

The present writer has long been aware, as have others (see Davison, 1925) that within the Cornish granites biotite is replaced by muscovite in the lode areas. Recent unpublished studies which he has made indicate that during this conversion Cu, Zn, As, Zn, Li, etc. are lost by the biotite, but the resulting muscovite contains at least as much Sn and Be, and sometimes more, than its parent. Further unpublished work on the greisenised granite of Cameron Quarry, St. Agnes, indicated that as greisenisation increased so the tin content of the rock rose from c. 20 p.p.m. to c. 650 p.p.m., but that when the greisen was locally converted to quartz the tin content of the latter was only 10 p.p.m. However cassiterite occurred in the quartz in voids after feldspar.

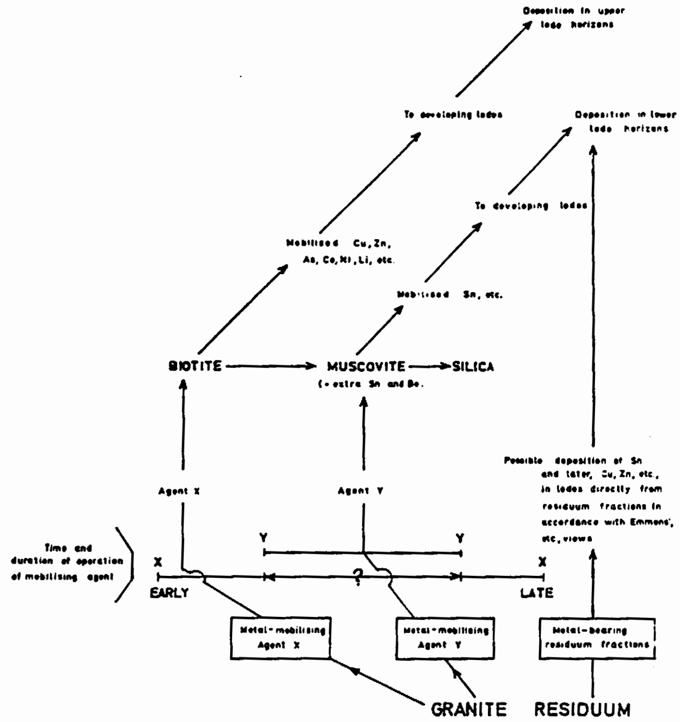


Fig. 2. Postulated genesis of Cornish tin lodes in which the ore metals are derived in part from the micas of the granites and in part directly from the residum (K. F. G. Hosking, 1963).

Clearly the widespread muscovitisation of biotite must lead to a release of large quantities of metal, and the silicification of muscovite causes the mobilisation of tin. What then happens to these mobilised elements? It seems at least reasonable to expect that they might migrate into fissures and contribute to the formation of lodes. Certainly the writer's work underlines that there is a source of lode metals other than the residuum, but it does not indicate the degree of importance of this source. There seems no reason why the hydrothermal deposits, at least, should not derive their ore-mineral components in part from the micas of the granite, and in part from the residuum, and this hypothesis is amplified in Fig. 2.

Mineralogical Aspect

The mineral species present in a given deposit, and their relative abundance, must depend on a number of factors of which those briefly discussed below are probably the most important. If it is assumed that the first step in the formation of such ore-deposits is the granitisation of pre existing rocks, followed perhaps by mobilisation of the granitic material and its subsequent crystallisation as granite or rhyolite, then it might well be (as hinted earlier) that the relative concentrations of the various elements available for the development of ore will vary from place to place because it is likely that there was considerable variation in the minor element content of the original crust of the Earth. That is to say, if the geological events in two widely-separated areas are identical any mineral deposits resulting may differ widely in mineralogical character and especially in the absolute amounts of the various elements concentrated in them. Secondly, the nature of tin deposits generally must depend on the degree of differentiation within the magma at the time of release of the ore-forming agents. Thirdly, mineralogical differences may accrue as a result of differences in the mineralogical character of the host rock. Fourthly, the composition of a given ore deposit will depend on when, and for how long, the channels along which the ore-forming agents moved were open. Fifthly, it will depend on the rate of flow of the agents. Sixthly, it will be governed by the presence or absence of obstacles in the channel ways which are capable of decreasing the flow rate and/or of causing "back-waters", and possibly turbulence, to develop. Seventhly, it will depend on the amount of fresh, and therefore exceedingly chemically reactive, faces, edges and corners developed along the channel ways as a result of cataclasis. Finally, but by no means the least important, the mineralogical nature of a given deposit will be governed to no small extent by the temperature /pressure conditions prevailing at the sites of deposition.

TABLE 6

SEQUENCE OF VEIN MINERALS IN THE XENOTHERMAL DEPOSITS OF CENTRAL BOLIVIA

(After Turneaure, 1960, 577)

Stages	1		2	3	4	5
Llallagua	q, (tm).	bm, cs, (wf), (ap).	frk, po, asp.	sl, (st), (cp).	mc, (asp), py, sd.	sd, sl, (py), wl(?).
Huanuni	q, tm, (ap), (fl).	cs.	(tl), po, asp.	sl, st, (cp).	py, mc, sd.	sd.
Morococala	q, tm, (tz).	cs.	tl, po, (asp).	sl, (st).	py, (mc), sd.	sd, sl, (py).
Potosi	q, py, cs, (asp), (wf), (bm).		st, (cp).	td, (sl), (mt), ad.	fo, rs, (gl).	aln.
Oruro	q, py, cs, (asp).		(sl), (cp), st.	td, ad.	fo, gl, frk.	kn, dk, aln, (q), (mc).

Minor minerals shown thus:- (wf).
Mineral abbreviations as follows:-

ad - andorite
aln - alunite
ap - apatite
asp - arsenopyrite
bm - bismuthinite
cp - chalcopyrite
cs - cassiterite
dk - dickite
fl - fluorite
fo - lead sulphosalts
frk - franckeite
gl - galena
kn - kaolinite
mc - marcasite
mt - matildite
po - pyrrhotite
py - pyrite
q - quartz
rs - ruby silver
sd - siderite
sl - sphalerite
st - stannite
td - tetrahedrite
tl - teallite
tm - tourmaline
tz - topaz
wf - wolframite
wv - wavellite

The broad paragenetic sequences of tin pegmatites, hypothermal lodes and replacements, and xenothermal deposits have much in common, and perhaps the greatest difference lies in the relative abundance of the species present. However, whilst certain species may occur in considerable quantity in all the deposits others tend to be confined to one particular type. Thus, whilst cassiterite and wolframite may be present in all the types of deposit, the tin-bearing sulphides (other than stannite) are virtually restricted to the xenothermal bodies, and minerals in which tantalum and niobium are dominant constituents (*e.g.* tantalite and columbite) are found only in pegmatites and as disseminations in granite. When, however, a given species occurs in more than one type of deposit it may possess both a trace-element "pattern" and a habit which are characteristic of the deposit in which it is found.

Generally speaking the earliest minerals of hypothermal deposits, and probably xenothermal ones also, tend to be deposited at the deepest horizons, nearest the source, but in the case of the large zoned pegmatites, which appear to have developed by fractional crystallisation within a closed system, the earliest species are deposited nearest the wall, but the latest species, which includes cassiterite, may have a more variable distribution: they may either report in the core or in and along fractures which developed in the earlier developed zones. In order that the broad similarities and differences may be appreciated three tables (4, 5, and 6) indicating the paragenesis of certain tin-bearing pegmatites, hypothermal and xenothermal deposits.

The type and degree of wall-rock alteration shows some variation according to the type of deposit with which it is associated and also with the original composition of the walls themselves. Pegmatites are often surrounded by a mica-rich, comparatively narrow halo, which, on occasion, may be fairly called greisen, whilst, as noted earlier, the early veins of the granitic cusps are characteristically bordered by narrow bands of greisen which may be modified by the addition of tourmaline, zinnwaldite, chlorite, fluorite and hematite. Commonly the granite between the greisen bands is kaolinised.

The "normal" hypothermal lodes and replacements are frequently bounded by wall-rock which has been subject to a number of different types of alteration: often the later alteration products develop, at least in part, at the expense of the earlier-formed secondary minerals. The normal sequence of alteration of granitic rocks and non-calcareous sediments is sericitisation, tourmalinisation, kaolinisation, chloritisation, and hematitisation, and associated with each, and sometimes occurring alone, is silicification. When the wall rocks are calcareous sediments or basic rocks they tend to be altered in the vicinity of orebodies, to a skarn-type suite of rocks in which axinite, epidote, zoisite, garnet, tremolite and calcite are commonly dominant*. All the zones of alteration noted above are often narrow and hence of limited value as indicators during the search for ore. However, for some considerable distance on either side of a given lode it is not unusual to find veinlets and partings fringed by the normal alteration minerals.

Such small features may assist in the search for lodes not only because they indicate that mineralisation has taken place in the area but more particularly because they tend to become more frequent as a lode is approached and to contain progressively greater concentrations of the lode metals (*e.g.* tin and copper) which can be readily revealed by geochemical methods of analysis (Hosking and Burn. unpublished studies, 1962). Associated with the obvious zone of wall-rock alteration adjacent to a tin lode there is also an envelope of rock, which is commonly broader, in which anomalous concentrations of the ore-forming metals were deposited during the time of ore-formation. This envelope can be revealed by geochemical analyses but, unfortunately, is often not greater than 20 ft. in width, and so again is not a particularly useful ore-indicator.

There is no doubt but that a study of the trace ore-metal content of wall-rock fractures is likely to reveal the presence of an orebody long before it is indicated by changes in the ore-metal content of samples of fissure-free rock.

* In skarn rock, in stanniferous areas, the tin may be confined to tin-bearing sphene and andradite garnet. This is so, for example, at the Red-a-ven Mine, to the north of the Dartmoor granite (Dearman and Sharkawi. Unpublished Studies, 1964). At Yala, Thailand, however, cassiterite occurs in a skarn but there also appreciable concentrations of tin occur in andradite. (Hosking. Unpublished Studies).

Finally, it has been indicated that lodes generally may be surrounded by an envelope of rocks which possesses anomalous thermoluminescent properties—due possibly to the precipitation of radio-active elements in them during the phase of ore-deposition (see Zeschke, 1963). However, studies of the granitic wall-rock adjacent to certain of the lodes at Geevor mine, Cornwall, indicated that anomalous thermoluminescence only occurred within 15 to 25 ft. of the orebody, as did anomalous concentrations of tin and copper, (Hosking and Usman Ahmad. unpublished studies, 1963). It seems likely, therefore, that the mineral explorationist can gain little by employing thermoluminescent techniques in granite terrain as aids to the location of tin deposits. However, the literature suggests that in limestones thermoluminescent haloes around lodes may be very large and so, in such an environment, establishment of their presence would be most rewarding.

Within tinfields some degree of lateral and/or vertical zoning is often, but not invariably encountered. In hypothermal fields, as in Cornwall, both lateral and vertical zoning may be prominent whilst in xenothermal fields, due perhaps to the tendency for fractures to be more widespread in the more superficial horizons, lateral zoning is usually dominant. Within pegmatite fields the mineralogic nature of the pegmatite may vary with the distance from the parent granite mass, and Mulligan (1962, p. 846) when discussing the origin of lithium and beryllium-bearing pegmatites, gives good field evidence in support of his contention that there is a relationship between the regional and internal zoning of such bodies and he states that the main indication of this "is the fact that the sequence of mineral assemblages from *innermost* to *outermost* dykes, in examples of regional zoning, is analogous to the sequence from *outermost* to *innermost* zones in examples of internal zoning."

That a similar relationship holds in some stanniferous pegmatite fields is indicated by the work of Agassiz (1954) in Kivu. There the outcropping tin-bearing bodies fall into three concentric zones around the parent granite. In zone 1, which is nearest to the granite, there are potassic pegmatites together with aplites and quartz veins containing Sn, W, Au, Nb, and Ta. In the intermediate zone 2 there are stanniferous sodium- and lithium-rich pegmatites, whilst in the outermost zone (3) quartz veins alone occur: these contain Sn, Au, Fe, As and S. Agassiz's diagrammatic section also suggests that the bodies may be vertically zoned, and one which at the surface may show zone 3 characteristics may display first zone 2 and then zone 1 features with increasing depth.

Hydrothermal Zoning

In Cornwall, which may be regarded as the "type region" of hydrothermal zoning, emanative centres are associated with cusps and around each the tin occurs in a zone which is commonly flatter than the neighbouring granite/country rock contact. This zone is overlain and in part overlapped by the copper/high temperature zinc zone which, in plan, is more extensive than the tin zone, and it, in turn, is "covered" in a lead/low temperature zinc zone. The zones are believed to have arisen as a result of the various minerals being deposited within certain limits of temperature (Dines, 1956, 1, 5-14). This zonal pattern is important to the searcher for tin deposits, in Cornwall and probably elsewhere, in that it indicates that the element is just as likely to occur in the invaded rocks as in the granite and that it cannot be expected to occur beneath the copper zone excepting near an emanative centre.

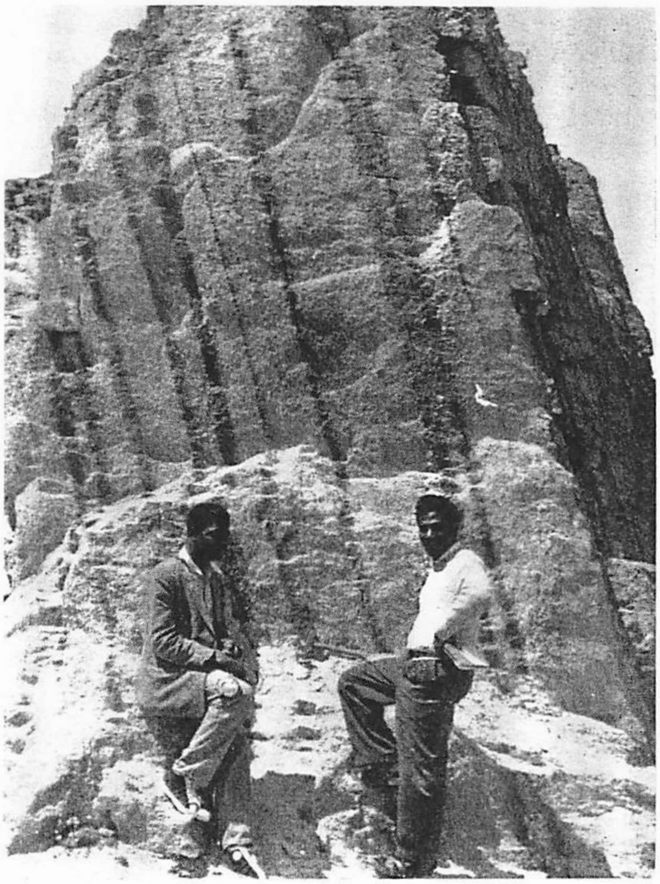


Fig. 3. Greisen bordered veinlets in kaolinised granite, Cligga, Cornwall.

The picture of primary zoning outlined is a very simplified one and though of considerable value during regional prospecting it can be misleading if too much emphasis is placed on it during the search for further tin-ore in an operating mine. Thus, whilst the top and bottom of the tin zone are approximately parallel in the Geevor/Levant mines, where the lodes trend approximately at right-angles to the granite/killas contact, at South Crofty mine, where the lodes parallel the contact, the writer has demonstrated (Hosking, unpublished studies) that the distance between the upper and lower economic limits of tin mineralisation varies markedly from lode to lode, and there the deposition of cassiterite has been controlled by a number of factors of which the temperature-gradient prevailing at the time of ore-formation was but one. Some of these other factors will be reviewed later. Furthermore, it is quite evident in Cornwall that neither the greisen-bordered veins nor the pegmatitic bodies fit into the primary zones of the normal hypothermal lodes. At South Crofty mine, for example, wolframite does not occur in the "normal" lodes below the 260 fathom horizon but it is present in considerable amount in 'pegmatitic' veins at and about the 335 fathom level. Failure to appreciate that what applied to hypothermal lodes did not apply to pegmatitic veins led some to conclude, quite erroneously, that cassiterite deposits were to be expected in these latter veins below the then lowest horizons of the mine.

Dewey (1948) claims that the thicknesses of the Cornish zones are as indicated in Table 7, but the present writer is of the opinion that these figures are very debatable and that certainly the tin width is generally excessive: in his opinion only on exceedingly rare occasions is the dip length of economic tin mineralisation of a major hypothermal lode in excess of 1,000 ft., and commonly it is several hundreds of feet less.

TABLE 7

THICKNESSES OF THE PRIMARY ZONES OF CORNWALL

(After Dewey, 1948)

	FEET
Zone of carbonates (iron, manganese, etc.)	400
Zone of sulphides of antimony, etc.	200
Zone of sulphides of lead and silver, giving place at depth to zinc and copper	1,800
Zone of sulphides of copper, intermixed with wolfram and tin for some 700 ft. at base	2,500
Zone of oxide of tin with wolfram in the upper parts	2,500

Because xenothermal deposits were formed comparatively near the surface under initially high temperature conditions, many of the deposits display marked telescoping and it is reasonable to expect, therefore, that if zoning is to occur it will be the lateral type which will be dominant. Turneaure (1960, p. 583) makes the following pertinent remarks: "Vertical zoning, marked by a consistent change in mineralogy with depth has not been clearly demonstrated in the (xenothermal) deposits of Central Bolivia, but some semblance of vertical zoning is noted in the tin-silver deposits of Potosi and Oruro. Lateral zoning, of the regional type, so well illustrated by the ore deposits of Northern Bolivia . . . is not evident in the mineralised belt of Central Bolivia, but lateral zoning on a local scale is suggested by mineral distribution at Llallagua and Huanuni". (The vertical zoning to which he refers is indicated at Potosi, for example, by the occurrence of silver above tin and of cassiterite above stannite). Concerning lateral zoning Turneaure states (*op. cit.*, p. 588) that at Llallagua the tin-bearing zone "is partly surrounded by one in which several low-grade sulphide veins have been explored", and at Huanuni, also, a tin zone is surrounded by one in which sulphides are dominant.

The ore shoots of these xenothermal deposits are similar in size to those of hypothermal lodes. Turneaure (*op. cit.*, pp. 583-584) notes that in Central Bolivia numerous ore-shoots in major veins have stope lengths of 200 to 300 m., and that the San Jose-San Fermi shoot, with a maximum stope length of 700 m., was undoubtedly one of the greatest tin shoots ever discovered.

Vertical Extent of Zones

Obviously the likely vertical extent of the tin zone must be taken into account when determining the possibility of finding ore below the lowest levels of operating and abandoned mines, though in the former the answer can often be facilitated by making an analysis of the structural controls (by means of Conolly diagrams, etc.) governing the location and extent of known orebodies in the mine and by consideration of the qualitative and quantitative metal and mineral changes with increasing depth. When the mine in question has been abandoned the answer must be obtained by consideration of data in available reports—which may be incomplete and unreliable if the mine is an old one—by examination of material on the waste dumps, by drawing comparisons with the depth of mineralisation in adjacent workings or well documented abandoned mines, and on fundamental geological considerations (such as the reasonable depth to which economic deposits of tin are likely to occur).

In extreme cases the last consideration may be the dominant one, and it was the one which was largely responsible for the writer arriving at the opinion that a long-abandoned, poorly documented mine in the Far East, which was only 300 ft. deep, and was situated at a granite slate contact, had no potential in depth. The decision derived from the fact that the granite occupied the low ground and the dominantly slate hill adjacent to the mine rose for *c.* 1,000 ft. above the shaft collar and contained tin-bearing veins—albeit, for the most part sub-economic—almost to its summit—*i.e.*, tin had been located over a vertical distance of *c.* 1,300 ft. (and over a horizontal distance of at least a quarter of a mile): there was, therefore, little likelihood of economic tin deposits occurring for any appreciable distance below the lowest levels of the mine and subsequent drilling confirmed this.

That the geoisothermal gradient may combine with other factors in determining the disposition and mineralogical distribution patterns of orebodies is exemplified by the disposition and character of the tin-bearing pipes of the Potgietersrus field of South Africa (see Strauss, 1954). There the pipes occur immediately below the Main granite in the domelike "roof" of the Lease and Bobbejaankop granites. Those pipes which are near vertical show a progressive mineralogical change downwards, but others which undulate along near horizontal planes approximately parallel to the geoisothermal surfaces assumed to be present at the time of ore-development consist of cassiterite-bearing zones separated by others of barren tourmaline. According to Strauss *op. cit.*, p. 144) the formation of this particular mineral distribution pattern depended "on whether any particular section of the pipe developed above or below the temperature where cassiterite crystallised."

Within the tin zone cassiterite and associated minerals are deposited most markedly wherever the rate of movement of the ascending ore-forming agents attains a critical velocity. Field evidence suggests that this velocity must be very low and is reached in the vicinity of marked constrictions. Such constrictions commonly occur at or near the junction of one rock type with another (because of marked differences in the degree and nature of fracture of the adjacent rocks); at places immediately below where the dip of a lode which has developed as a result of mineralisation of a normal fault decreases and so below where the channel is constricted; and at the intersections of lodes where the velocity of the mineral-depositing agents is lessened because of the presence of cataclastic products and where chemical reaction is enhanced because of the presence of fresh, and therefore very chemically reactive, rock-edges, -corners and -faces.

At South Crofty mine, Cornwall, for example, the No. 9 lode fades out as it passes from the granite across the slate/porphyry junction, and the No. 12 lode, which is a small rich irregularly shaped replacement deposit, is confined to the upper horizons of a granite tongue. It has developed from agents which ascended via a channel-way which in the underlying slate is virtually barren. At the Magdalen mine, Ponsanooth, cassiterite was deposited preferentially within a dolerite where a lode intersected it, and at the Wherry mine a similar thing happened where a porphyry dyke was intersected. At Parbola a tin-bearing stockwork (as noted earlier) developed entirely in a prophyry dyke, and the Complex Lode of the Roskear Section of South Crofty consists of a wolframite/arsenopyrite-bearing pegmatite which, having been severely fractured, became a centre for cassiterite deposition. At Cligga, the greisen-bordered vein-swarm soon dies out on passing from the granite into the hornfels. Scores of other similar examples could be sited from other tinfields.

It is self-evident that lodes developed where fractures formed which were sufficiently extensive to tap the ore-forming agents, and that such fractures formed along planes of maximum weakness. From the point of view of the mineral explorationist it is important to appreciate that the general places in which such fractures could occur, and so in which lodes might be found, are, on occasion, indicated by the presence of earlier-developed fracture controlled rock bodies such as porphyry dykes. The porphyry dykes developed in areas where fracture was easiest, and such areas continued to be ones of easy fracture during the early stages of ore-development. At South Crofty mine swarms of rich tin-bearing veins occur within a larger plexus of earlier felspathic wolframite and arsenopyrite veins. Here again an area which was readily fractured at a particular stage continued to possess this property at a later stage; thus, in this mine, the location of further felspathic veins will immediately indicate an area to be explored intensively for a swarm of tin-bearing veins. (Hosking, unpublished studies.)

Tin in Pegmatites

The occurrence of cassiterite in pegmatites requires special consideration. In large typically zoned pegmatites available evidence indicates that cassiterite is deposited from the last of the pegmatite fluid, usually by replacement. It may, therefore, occur in varying amounts in a number of earlier zones if these were fractured before the consolidation of the body was complete, or, in the absence of such fracture, it will be confined to the core. Clearly, evaluation of the tin potential of these pegmatites by drilling, etc., is extremely difficult. However, there are pegmatites and pegmatites, and one tin-bearing group is characterised by the fact that the cassiterite tends to accumulate in the high spots beneath the roof. Derry (1930) describes several such examples from Eastern Manitoba in which cassiterite is markedly concentrated in the apical parts of arch-shaped pegmatites, and he is of the opinion that the mineral was developed early as a result of tin-rich volatiles rising into the roof and being entrapped there. (The accumulation of tourmaline under much the same circumstances occurred at Porthmeor, Zennor, Cornwall.

Agassiz (*op. cit.*, pp. 45-47) also describes certain kaolinised stanniferous pegmatite dykes in which the cassiterite is concentrated near the roof. Concerning the Mumba example he says "Elle est faiblement chargée de cassitérite fine et noire, et sillonnée de filonnets lenticulaires constitués par du quartz et de la lépidolite rose. Vers le toit du filon, ces lentilles peuvent prendre de l'importance et se chargent de cassitérite. La roche est alore, constituée par du quartz, de la lépidolite rose, de la topaze incolore et de la cassiterite noire." In connection with a further pegmatite he notes (p. 47) that "des formations de quartz—muscovite minéralisées en cassitérite se trouvent en lentilles a san toit."

Concerning the cassiterite concentration pattern in pegmatites a further variation occurs in the flat-dipping examples at Kamativi (Southern Rhodesia) where, according to Fick (1960, p. 479) "normally, the greater concentration of cassiterite occurs just above the quartz-mica footwall selvedge. . . . Pegmatites with a high cassiterite concentration near the hanging-wall selvedge are less common."

It is important to recognise that the cassiterite in a pegmatite may be truly pegmatitic in origin or it may have been introduced during a later hypothermal phase. Individual

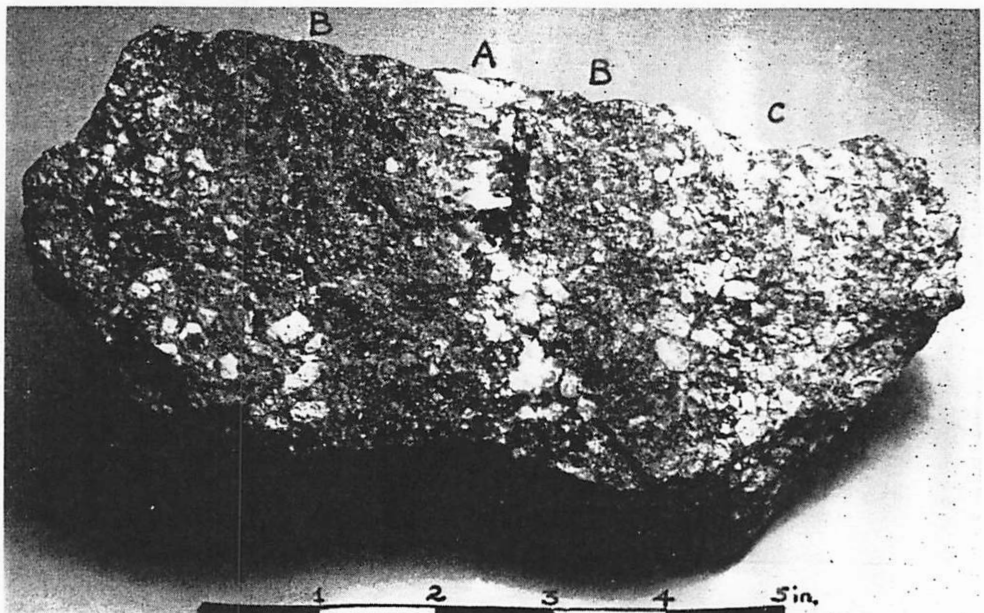


Fig. 4. Quartz vein (A) containing cassiterite bordered by greisen (B) in kaolinised granite (C), Cligga.

5. *Dull brown cassiterite tals in quartz-sericite matrix, Karogwe, Tanzania.*

gmatites containing only "pegmatite" cassiterite are often b-economic although it may be profitable to work a series such bodies simultaneously on a large tonnage low grade isis. However, a pegmatite which has behaved as a favourble host for the precipitation of cassiterite during the ypothe al stage may be a rich tin-ore body. Careful apping, the habit of the cassiterite, and microscopic studies ay, n occasion, permit the nature of the tin mineralisation be established at a fairly early stage in the investigation f the pegmatite.

Mineralogical Characteristics

The mineralogical aspect of tin deposits cannot be concluded without mentioning certain physical characters of cassiterite which, on occasion, might facilitate the search for ore.

Cassiterite, which crystallises in the tetragonal system, nay display a variety of habits, and some of these are only foun in certain types of deposit. True pegmatite cassiterite onsists of squat dipyramids (101) and (111): cassiterite rystals of greisen-bordered veins and early cassiterite of nica-selvedged veins, often with abundant tourmaline, aloing granitic cusps are short prismatic (with (100) and 110) prominent) and are terminated by squat dipyramids. n all other deposits the cassiterite crystal tends most commony to be long prismatic, often with acute pyramidal terminitions ut on occasion the acute dipyramids may completely clipse the prisms (as locally, at South Crofty mine).

Contrary to many statements* wood tin, which may have leveloped as a result of crystallisation of a gel, is not confined o primary deposits which have developed at comparatively ow temperatures near the surface, nor is there any certain vidence known to the writer in support of the contention f others (see Jones, 1925, pp. 40-41, and Goldschmidt, 1954, . 395) that is may develop from tin liberated from stannite y supergene action. Wood tin certainly occurs in subolcanic deposits (as in Mexico) but it also reports, in Cornwall, in the early felspathic hypothermal veins of the Garth mine which were formed at considerable depths and probably at fairly high temperatures. Furthermore, at West Wheal Kitty (St. Agnes, Cornwall) not only are aggregates of wood tin locally fringed by acicular crystals of "normal" cassiterite, but the former are also veined, and in part replaced, by sphalerite containing ex-solution bodies of chalcopyrite (Hosking, unpublished studies). Unmixing of the sulphides probably took place between 400 and 350 deg. C. (Sugaki and Yamae, 1952), and as there is not the slightest indication that the ore in question developed under conditions of increasing temperature, it can only be concluded that the wood tin is truly hypothermal. In Cornwall there is strong evidence that when stannite is decomposed in the zone of oxidation wood tin is not developed but much, if not all, of the liberated tin reports at the site of deposition as varlamoffite, a soft clay-like, cream to brownish colloidal material which, in the opinion of Russell and Vincent (1952, p. 822) is probably a mixture of "cassiterite and hydrated stannic oxide, with other impurities in a very fine state of division."

Similar material has been derived from stannite in the Belgian Congo, and at Chenderiang (Malaya) it coats cassiterite crystals, though here a stannite parentage has not been demonstrated, and it is associated with another secondary tin-mineral whose approximate composition is (CaO, SnO, SiO_2) (tin sphene?). This latter species, which tends to develop at quartz cassiterite contacts, is probably a product of late hypogene activity, and the following statement concerning its genesis appears in a report by the Mineral Resources Division (see Ingham and Bradford, 1960, p. 105): "It appears probable that following the crystallisation of quartz and cassiterite, these minerals were attacked along the cassiterite-quartz boundary by the passage of active mineralisers containing lime. Unique conditions were produced and the environment was favourable for the crystallisation of calcium-tin-silicate". The possibility that the Chenderiang varlamoffite may have been derived directly from cassiterite, or possibly via the new lime-bearing species cannot be entirely dismissed, as Kohanowski (1953), working on South American tin-ore, has demonstrated that at room temperature cassiterite can go into solution colloidally.

Edwards and Baker (1954) have demonstrated that in the zone of secondary sulphide enrichment in the Sardine Tin mine, Queensland, as stannite is converted to covellite and

Chukhrov, for example, states that quartz and feldspar-quartz veinlets with ssiterite and hematite occur in the Shahshagaily deposit which is confined to the ide shatter zone in the medium grained granites of the eastern contact of the aibian granite mass in Betpakdala. Small amounts of scheelite, fluorite, adularia, d rare pyrite, chalcopyrite, and topaz also occur in the veinlets. The enclosing cks are chloritised and hematitised. Cassiterite and some of the quartz show lloform structures—*which indicate their near surface origin.*—The observed culiarities of the mineral composition permit us to draw the conclusion that in e formation of veinlets with colloform cassiterite and hematite, mixing of magatogene solutions with meteoric waters enriched in oxygen, due to a relative oximity to the surface, was of great importance.

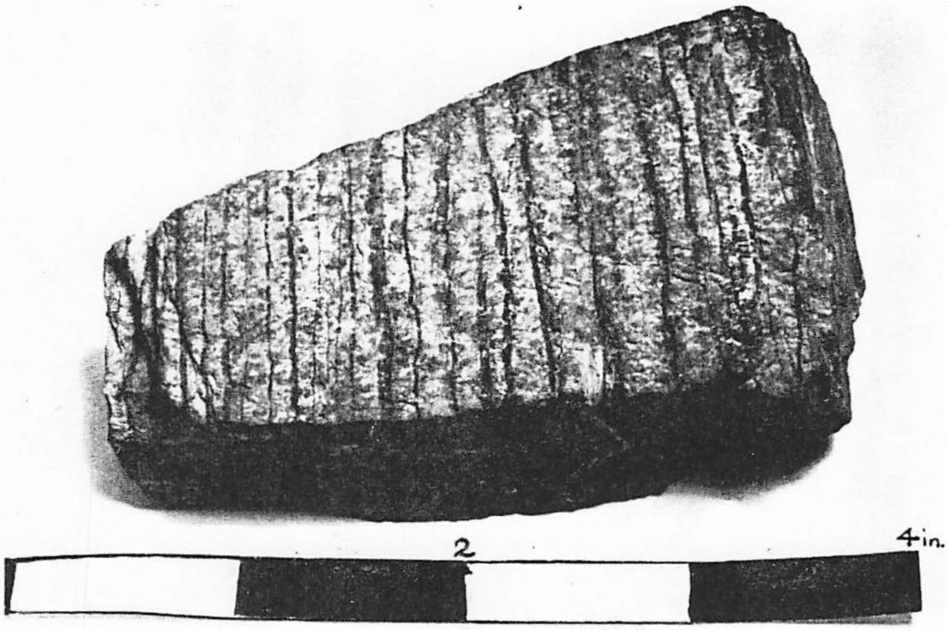


Fig. 5. *Veinlets of cassiterite, quartz, and minor tourmaline in slate hornfels, Polperro, Cornwall.*

chalcocite, secondary cassiterite (not wood tin) appears "as minute granules and needle-like crystals, precipitated in the veinlets of secondary copper sulphides, or as outgrowths on the coarser crystals of primary cassiterite". These workers further observe that "the amount of such secondary cassiterite is not always sufficient to account for the amount of tin set free during the replacement of the stannite, and it is concluded that the additional tin migrated with the iron set free from the stannite, and not incorporated in the covellite and chalcocite. The secondary cassiterite persists as such in the zone of oxidation, and some of the migrating tin may have accumulated here also, but the tin assays of the oxidised ore and the primary ore do not point to any significant tin enrichment in the oxidised zone comparable with its enrichment in copper (p. 78).

From the above it is clear that examination of the habit of cassiterite occurring in alluvial/eluvial deposits may indicate that the species was derived wholly, or in part, from pegmatites, greisen-bordered or similar early deposits, or from other hydrothermal deposits. Contrary to the suggestion implicit in Petersen's paper (1960) it will not enable one to make more precise statements concerning the parentage.

It is not necessary to discuss the twinning characteristics of cassiterite as they are of little or no help to the prospector, but it is worth noting that the maximum size of individual cassiterite crystals tends to decrease as one passes from pegmatites, via the greisen-bordered, and similar, veins to the other hydrothermal bodies.

Within a given mine the colour zones of cassiterite may show significant variation from one lode to another and at South Crofty mine (Cornwall) this has, on occasion, facilitated the correlation of lode branches separated by blocks of unworked ground (Hosking, unpublished studies). As the lodes of this mine, in common with others, were not developed at precisely the same time, variations in the cassiterite, of the type noted above, are to be expected. However, this technique of lode correlation has to be used cautiously as the Cornish lodes, at any rate, commonly contain 2 or 3 generations of cassiterite and as yet not enough is known about the variations in the nature of the cassiterite within a given lode. Nevertheless, over short distances correlations which have subsequently been proved by mining to be correct have been achieved by considering solely the colour characteristics of the cassiterite developed immediately before the chlorite. The early-developed cassiterite, which is commonly associated with tourmaline in this mine, is invariably a pale brown and of no value in work of the type under discussion.

Whilst discussing colour it is also relevant to mention that if cassiterite is heated to *c.* 1,000 deg. C. for about 10 min., and then cooled its colour is altered. Dark cassiterite changes to orange/vermilion and the white Malayan variety with occasional red (hematite?) partings becomes pink; such heat-treated cassiterite may fail to react to the tinning test described later. During the drilling of alluvials in the Bissoe Valley (Cornwall) this colour change enabled the writer to state that some of the cassiterite obtained immediately above the bed-rock had been carried down from the surface and was derived from the tailings of an arsenic calcination plant further up the valley. It is also worth noting that whilst a gentle heat does not affect the colour of cassiterite it causes brownish zircon, such as occurs in the Malayan alluvials, to become colourless. This fact is made use of by Chinese miners to differentiate between fine-grained samples of these two species.

It is also to be noted that cassiterite may be about as magnetic as columbite and so in Malaya and Nigeria, for example, the possible presence of the species in the magnetic fractions must not be ignored. One simple method of separating magnetic cassiterite from columbite depends on the fact that when these minerals are heated to *c.* 1,000 deg. C. for about 10 min. and then cooled, the cassiterite, but not the columbite, ceases to be magnetic.

Mention must also be made of the fact that apart from the chemical inertness of cassiterite the main reason why marked alluvial concentrations of this mineral can develop is its comparatively high specific gravity (6. 8-7. 1). The high specific gravity of cassiterite often permits the mineral to be rapidly and simply separated by "gravity methods" from the species with which it occurs in alluvial deposits and in samples of crushed rock. Hence it is understandable why panning, vanning and allied methods have played a major role in the search for tin deposits.

(To be concluded)